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The Quark-Antiquark Asymmetry of the Nucleon Sea from Λ and $\overline{\Lambda}$ Fragmentation

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Abstract

We present a general analysis of the spin transfer for Λ and $\overline{\Lambda}$ production in deep-inelastic scattering of polarized charged leptons on the nucleon, and find that the pattern of different behaviors of Λ and $\overline{\Lambda}$ production observed by the E665 Collaboration suggests the possibility of quark-antiquark asymmetries either in the quark to Λ fragmentation functions and/or in the quark and antiquark distributions of the target proton. We also point out that the strange-antistrange asymmetry of the nucleon sea may produce an observable contribution to the different behaviors of Λ and

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$\overline{\Lambda}$ production. We find that a softer $\overline{s}(x)$ than $s(x)$ as predicted by the light-cone baryon-meson fluctuation model of intrinsic quark-antiquark pairs of the nucleon sea might lead to a reasonable picture. However, the magnitude is still too small to explain the E665 data and the conclusion has also strong model-dependence. This may suggest the importance of quark-antiquark asymmetry in the quark to Λ fragmentation functions, provided that the E665 data are confirmed.

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It is well known that the production of Λ and $\overline{\Lambda}$ in deep-inelastic scattering (DIS) of lepton on the nucleon may provide information on the quark content of the target nucleon [1, 2], as well as on the quark to Λ fragmentation functions [3, 4]. The idea that the fragmentation of the Λ hyperon in DIS of a charged lepton on a nucleon target can supply information concerning the strange content of the nucleon was originally proposed in Refs. [1, 2]. There are four different combinations of the polarizations of the charged lepton beam and the nucleon target:
i) both the lepton beam and the nucleon target are unpolarized;
ii) the nucleon target is polarized while the lepton beam is unpolarized [1, 2, 3];
iii) both the lepton beam and the nucleon target are polarized [5];
iv) the lepton beam is polarized while the nucleon target is unpolarized [3].
These different combinations provide different information concerning the quark distributions and quark to Λ fragmentation functions. It is suggested in Ref. [3] that there are still large uncertainties in the quark to Λ fragmentation function, and it is practically more urgent to measure the Λ fragmentation functions before using the Λ fragmentation to probe the quark content of the nucleon. Indeed, some symplifying assumptions about the quark to Λ fragmentation functions were found to be of little predictive power when applied to Λ production in e^+e^- annihilation process at the Z resonance [6, 7], and to semi-inclusive Λ production of polarized charged lepton DIS process on the nucleon target [8].

However, there have been recent progress [9, 10, 11] in order to understand the quark to Λ fragmentation functions by connecting them with the quark distributions inside the Λ by the Gribov-Lipatov relation (GLR) [12]:

$$D_q^h(z) \sim q_h(x) \ , \tag{1}$$

where $D_q^h(z)$ is the fragmentation function for a quark q splitting into a hadron h with longitudinal momentum fraction z, and $q_h(x)$ is the quark distribution for finding the quark q inside the hadron h carrying a momentum fraction x. D_q^h and q_h depend also on the energy scale Q^2, and this relation holds, in principle, in a certain Q^2 range and in leading order approximation. It is shown recently [13] that the Gribov-Lipatov relation is also verified to hold in leading order for the space- and time-like splitting

functions of QCD. Moreover, although Eq. (1) is only valid at $x \to 1$ and $z \to 1$, it provides a reasonable guidance for a phenomenological parametrization of the various quark to Λ fragmentation functions. We are encouraged to find that the predictions of the quark to Λ fragmentation functions in an SU(6) quark-diquark model [14] and in a pQCD based model [15] are in good agreement with the experimental data on Λ production in both the e^+e^- annihilation process at the Z resonance [10] and in polarized positron beam DIS on a nucleon target [9, 11]. Thus we have at least some reasonable parametrizations of quark to Λ fragmentation functions, though there are still large uncertainties in the flavor and spin decompositions of these fragmentation functions.

For a longitudinally polarized charged lepton beam and an unpolarized nucleon target, the longitudinal spin transfer to the Λ is given in the quark parton model by [3]

$$A^{\Lambda}(x,z) = \frac{\sum\limits_q e_q^2 [q^N(x,Q^2) \Delta D_q^{\Lambda}(z,Q^2) + (q \to \overline{q})]}{\sum\limits_q e_q^2 [q^N(x,Q^2) D_q^{\Lambda}(z,Q^2) + (q \to \overline{q})]} \ . \tag{2}$$

Here $y = \nu/E$, $x = Q^2/2M_N\nu$, and $z = E_\Lambda/\nu$, where $q^2 = -Q^2$ is the squared four-momentum transfer of the virtual photon, M_N is the proton mass, and ν, E, and E_Λ are the energies of the virtual photon, the target nucleon, and the produced Λ respectively, in the target rest frame; $q^N(x,Q^2)$ is the quark distribution for the quark q in the nucleon, $D_q^{\Lambda}(z,Q^2)$ is the fragmentation function for Λ production from quark q, $\Delta D_q^{\Lambda}(z,Q^2)$ is the corresponding longitudinal spin-dependent fragmentation function, and e_q is the quark charge in units of the elementary charge e. In a region where x is large enough, e.g. $x > 0.2$, one can neglect the antiquark contributions in Eq. (2), and probe only the valence quarks of the target nucleon. On the contrary, if x is much smaller, one is probing the sea quarks and therefore the antiquarks must be considered as well. For $\overline{\Lambda}$ production the spin transfer $A^{\overline{\Lambda}}(x,z)$ is obtained from Eq. (2) by replacing Λ by $\overline{\Lambda}$. The Λ and $\overline{\Lambda}$ fragmentation functions are related since we can safely assume matter-antimatter symmetry, *i.e.* $D_{q,\overline{q}}^{\Lambda}(z) = D_{\overline{q},q}^{\overline{\Lambda}}(z)$ and similarly for $\Delta D_{q,\overline{q}}^{\Lambda}(z)$.

Recently, the HERMES Collaboration at DESY reported the result of the longi-

tudinal spin transfer to the Λ in polarized positron DIS on the proton [16]. Also the E665 Collaboration at FNAL measured the Λ and $\overline{\Lambda}$ spin transfers from muon DIS [17], and they observed very different behaviour for Λ and $\overline{\Lambda}$ polarizations. The E665 data for the spin transfer are presented as function of the Feynman variable x_F, although $x_F \approx z$ is a good approximation in the kinematic range of the E665 experiment [11]. Strictly speaking, the magnitude of the measured spin transfer Eq.(2) should be less than unity; thus the E665 data, whose range of magnitude for the measured spin transfer is larger than unity, are of poor precision. But the different behaviors of the Λ and $\overline{\Lambda}$ spin transfer might still be a realistic effect. Both the HERMES data and the E665 data are measured for $x_F > 0$, which corresponds to the current fragmentation region. Thus it is natural to try to understand the data from the viewpoint of current fragmentation, rather than target fragmentation as suggested by E665. We will focus our attention on the different behavior of the Λ and $\overline{\Lambda}$ spin transfer in the E665 data.

It is interesting to notice that the fragmentation functions from the quark-diquark model [9, 10] can give very good descriptions of both the data of Λ fragmentations in e^+e^- annihilation at the Z resonance [10], and in polarized positron DIS on the unpolarized proton by HERMES [9], with only naive parameters without any adjustment. Although the Gribov-Lipatov relation should be of poor validity at small x, the fragmentation functions obtained by using it in the quark-diquark model seem to give a reasonable relation between different quark to Λ fragmentation functions. We would like to mention that the fragmentation functions derived in a quark-diquark picture [18] and in an MIT model framework [19] arrived at similar qualitative results as in Ref. [9], although the explicit shapes are not the same. Therefore we first use the fragmentation functions from the quark-diquark model as input in order to calculate the spin transfer, Eq. (2), for the Λ and $\overline{\Lambda}$ production.

We use the recent CTEQ5 parametrizations as input for the quark distributions of the nucleon [20]. In Fig. 1(a) we present the calculated results for the spin transfer of Λ and $\overline{\Lambda}$, and compare the results with the the HERMES and E665 data. We notice that the calculations show a trend of increasing positive polarization with increasing z that seems to be suggested by the data. This supports the prediction of positive polarized u and d quarks inside Λ at large x [9, 10]. However, the calculations cannot

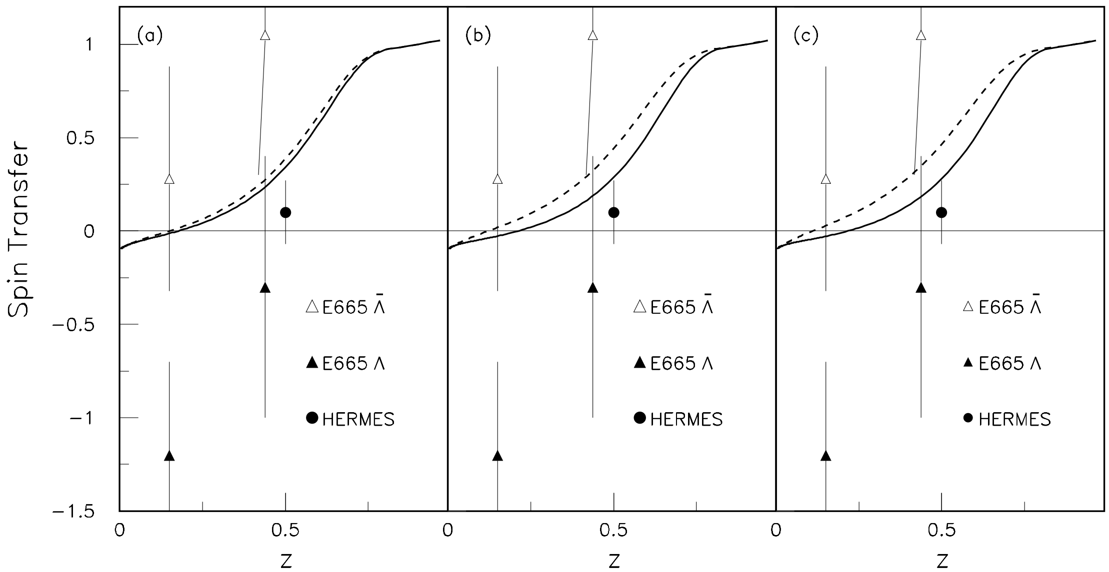

Figure 1: The z-dependence of the Λ and $\overline{\Lambda}$ spin transfer in polarized charged lepton DIS on the nucleon. The solid and dashed curves correspond to the calculated results of Λ and $\overline{\Lambda}$ spin transfers with: (a) the CTEQ5 set 1 parametrization of quark distributions [20]; (b) the modified CTEQ5 set 1 quark distributions including only strange-antistrange asymmetry Eq. (12); (c) the modified CTEQ5 set 1 quark distributions including an additional contribution of $\overline{d}(x) > d(x)$ in the target proton Eq. (13). The quark to Λ fragmentation functions are predicted by the light-cone SU(6) quark-diquark model, and the average value of the Bjorken variable is chosen as $x = 0.005$, corresponding to the E665 average value.

produce a difference of the spin transfers for Λ and $\overline{\Lambda}$ as observed by E665. Our results are also in qualitative agreement with a Monte Carlo simulation based on the naive quark model and a model with SU(3) symmetry [21], where the different behavior of spin transfer for Λ and $\overline{\Lambda}$ are not predicted. Although the effect due to target fragmentation has been suggested as a possible mechanism for the E665 different behavior of Λ and $\overline{\Lambda}$ production [17], the kinematic region for Λ and $\overline{\Lambda}$ production corresponds to $x_F > 0$, which is the current fragmentation region [11]. Thus we need to find a new mechanism for the different behavior of Λ and $\overline{\Lambda}$ production. The possibility of a quark-antiquark asymmetry in the fragmentation functions has been investigated in Ref. [11], and the purpose of this paper is to investigate possible asymmetries in the quark distributions of the nucleon target.

Let us consider the spin transfer for Λ and $\overline{\Lambda}$ production in a region where the sea dominates, namely where the Bjorken x is rather small, like in the E665 experiment, which has $\langle x_B \rangle$=0.005. The E665 data indicates that in this region and for z between 0.1 and 0.5, one has

$$A^{\overline{\Lambda}}(x,z) >> A^{\Lambda}(x,z). \tag{3}$$

Let us consider several possible situations:

1) The sea is fully symmetric, namely $q(x) = \overline{q}(x)$, for all flavors u, d, s. This implies clearly $A^{\overline{\Lambda}}(x,z) = A^{\Lambda}(x,z)$, which contradicts the data.

2) The sea is not fully symmetric, and in this case one can consider several scenarios:

(a) One flavor dominates, for example u-quark. Let us define

$$\Delta\overline{Q} = \overline{q}(x)[\Delta D_q^{\Lambda}(z) + \Delta D_{\overline{q}}^{\Lambda}(z)] \quad , \quad \overline{Q} = \overline{q}(x)[D_q^{\Lambda}(z) + D_{\overline{q}}^{\Lambda}(z)] \ . \tag{4}$$

In this case, if the sea is symmetric we are back to case 1) above and Eq. (3) cannot be satisfied. If the sea is not symmetric, namely $u = \overline{u} + \epsilon$, we have

$$A^{\Lambda} = \frac{\epsilon \Delta D_u^{\Lambda} + 2\Delta\overline{U}}{\epsilon D_u^{\Lambda} + 2\overline{U}} \ , \tag{5}$$

and

$$A^{\overline{\Lambda}} = \frac{\epsilon \Delta D_{\overline{u}}^{\Lambda} + 2\Delta\overline{U}}{\epsilon D_{\overline{u}}^{\Lambda} + 2\overline{U}} \ . \tag{6}$$

Let us try to see what conditions one must have in order to fulfill Eq. (3). It seems clear that $D_u^{\Lambda} >> D_{\overline{u}}^{\Lambda}$, therefore if $\epsilon > 0$ (which is the case for $x = 0.005$ in present parametrizations of quark distributions), Eq. (3) will be satisfied provided

$$\Delta D_{\overline{u}}^{\Lambda} >> \Delta D_u^{\Lambda} \ , \tag{7}$$

a condition which is assumed and discussed in [11] as a possibility to explain the different behaviors of Λ and $\overline{\Lambda}$ productions in the E665 data.

(b) All three flavors contribute but only one is asymmetric, say u, whereas $d = \overline{d}$ and $s = \overline{s}$. This case is similar to the previous one, since we have

$$A^{\Lambda} = \frac{4\epsilon \Delta D_u^{\Lambda} + X}{4\epsilon D_u^{\Lambda} + Y} \ , \tag{8}$$

and

$$A^{\overline{\Lambda}} = \frac{4\epsilon \Delta D_{\overline{u}}^{\Lambda} + X}{4\epsilon D_{\overline{u}}^{\Lambda} + Y} \ , \tag{9}$$

where $X = 8\Delta\overline{U} + 2\Delta\overline{D} + 2\Delta\overline{S}$ and $Y = 8\overline{U} + 2\overline{D} + 2\overline{S}$. We reach the same conclusion as above, and since the asymmetric flavor can be either d or s, it seems that one should have more generally

$$\Delta D_{\overline{q}}^{\Lambda} >> \Delta D_{q}^{\Lambda} \ , \tag{10}$$

a condition which has been discussed and considered in [11]. Remember that positivity implies $D_{\overline{q}}^{\Lambda} \geq \Delta D_{\overline{q}}^{\Lambda}$, so it means that one should have a strong bound on ΔD_{q}^{Λ}, namely

$$D_{\overline{q}}^{\Lambda} >> \Delta D_{q}^{\Lambda} \ . \tag{11}$$

However, the situation will be different in case we have $\epsilon < 0$, which means that $\overline{q}(x) > q(x)$. The strange quark-antiquark asymmetry predicted by the light-cone baryon-meson fluctuation model [23] introduces such a behavior for the strange quarks and antiquarks. Thus the pattern of the difference in the Λ and $\overline{\Lambda}$ productions in the E665 data could suggest a possibility of $\overline{q}(x) > q(x)$ in the target proton.

The CTEQ parametrizations of quark distributions are based on data of various structure functions from different DIS processes obtained in the last three decades. The light-flavor u and d content of the nucleon is well constrained and the uncertainties are not big, though there are still a number of phenomenological anomalies related to the spin and flavor content of the nucleon sea [23]. However, the strange content of the nucleon is less known than the light-flavor u and d quarks. In the CTEQ parametrizations, identical strange and antistrange quark distributions are assumed. However, it is pointed out in Ref. [23] that within the allowed errors, the CCFR data of $s(x)/\overline{s}(x)$ [24] does not rule out a strange-antistrange asymmetry, as suggested by the light-cone baryon-meson fluctuation model [23]. Moreover, this light-cone baryon-meson fluctuation model of intrinsic quark-antiquark ($q\overline{q}$) pairs in the nucleon sea suggests a soft $\overline{s}(x)$ compared to $s(x)$ (i.e., $\overline{s}(x) > s(x)$ at small x and *vice versa* at large x). Remember that a softer $\overline{s}(x)$ than $s(x)$ was predicted by Burkardt and Warr [25] from the chiral Gross-Neveu model at large N_c in the light-cone formalism. It is also pointed out in Ref. [23] that the conflict between

two different determinations of the strange quark distributions [26, 27] could be a phenomenological support for $s(x) \neq \overline{s}(x)$, or more explicitly, a softer $\overline{s}(x)$ compared to $s(x)$. Another phenomenological support for a softer $\overline{s}(x)$ is also suggested by Barone, Pascaud, and Zomer [28] from a global QCD analysis of structure functions, including neutrino DIS data. More recently, Buccella, Pisanti, and Rosa [29] found, from their analysis of the new CCFR data on structure functions at small x, an alternative independent support for a softer $\overline{s}$, in agreement with the prediction of Ref. [23]. Therefore we can check the possibility that the different behavior of spin transfer for Λ and $\overline{\Lambda}$ come from the strange-antistrange asymmetry of the nucleon sea. Indeed, the E665 data are measured corresponding to the quark distributions of the nucleon in the Bjorken variable range $0.0001 < x < 0.1$ with $\langle x \rangle = 0.005$, where the antiquark distributions are of the same order as those of the quark distributions. From the light-cone baryon-meson fluctuation model [23] we know that the antistrange quark distribution could be as big as more than two times that of the strange quark distribution at small x. Therefore we can modify the strange and antistrange quark distributions of the CTEQ parametrization and check the role played by the strange-antistrange asymmetry for the Λ and $\overline{\Lambda}$ productions.

We choose the values of the quark distributions with quark-antiquark asymmetry of the nucleon sea at $x = 0.005$ as

$$\begin{aligned} u &= u_0 + \delta u = 50.32; \\ d &= d_0 + \delta d = 45.41; \\ s &= s_0 + \delta s = 17.11 - 8; \\ \overline{u} &= \overline{u}_0 + \delta \overline{u} = 33.55; \\ \overline{d} &= \overline{d}_0 + \delta \overline{d} = 35.29; \\ \overline{s} &= \overline{s}_0 + \delta \overline{s} = 17.12 + 8; \end{aligned} \tag{12}$$

where q_0 and δq ($q = u, d, s, \overline{u}, \overline{d}, \overline{s}$) are the quark distributions of CTEQ parametrization at $x = 0.005$ and the corresponding modifications, respectively. In principle we can also introduce the nucleon sea quark-antiquark asymmetry in the light flavor u and d quarks, but we still have no phenomenological evidence for doing this. In comparison, there are large uncertainties concerning the strange and antistrange content

of the nucleon sea. Therefore we first check the role played by the strange-antistrange asymmetry in the nucleon target for the difference between Λ and $\overline{\Lambda}$ productions in polarized charged lepton scattering on the nucleon. We present in Fig. 1(b) of the calculated results with strange-antistrange asymmetry. It is interesting to find that the strange-antistrange asymmetry of the nucleon sea predicted by the light-cone baryon-meson fluctuation model can indeed produce a trend for the different behaviors of the spin transfers for Λ and $\overline{\Lambda}$ production observed by E665, though the magnitude is still not enough to explain the data.

From Eq. (2), we find that the different strange and antistrange quark distributions of the nucleon sea are the reason for the different Λ and $\overline{\Lambda}$ production. The u and d ($\overline{u}$ and $\overline{d}$) quarks mainly contribute to the background of the Λ ($\overline{\Lambda}$) production. In the quark-diquark model of the quark to Λ fragmentation functions [9, 10], the quark helicities of u and d quarks have almost zero net contribution in the whole x range $0 \rightarrow 1$. But this does not seem to be true from the SU(3) symmetry argument that the u and d quarks may have net helicilities of the order of -0.2 [22]. Therefore the absolute values of the spin transfers at small z might not be correctly predicted by the quark-diquark model parametrization of quark to Λ fragmentation functions [9, 10]. The interesting aspect is the difference of the Λ and $\overline{\Lambda}$ productions from the strange-antistrange asymmetry of the nucleon sea. From Fig. 1(b) we notice that the magnitude of the difference can be the order of 0.25, which should be large enough to cause an observed difference in the measurements of Λ and $\overline{\Lambda}$ productions in polarizied charged lepton DIS process on the nucleon. This shows that the strange quark content of the nucleon could be probed after we carefully consider the effect of u and d quarks and antiquarks of the nucleon, and of various quark to Λ fragmentation functions.

We would like to mention that the above conclusion depends on the specific forms of the quark to Λ fragmentation functions used as input for the spin transfer. We also present in Fig. 2(a) and (b) the calculated results with and without strange-antistrange asymmetry of the nucleon sea, but with the fragmentation functions from a pQCD based model [15] which is also good in describing the data of Λ production in e^+e^- annihilation at the Z resonance [10] and in the polarized positron DIS on the proton by HERMES [9, 11]. We notice that the difference between the spin transfer

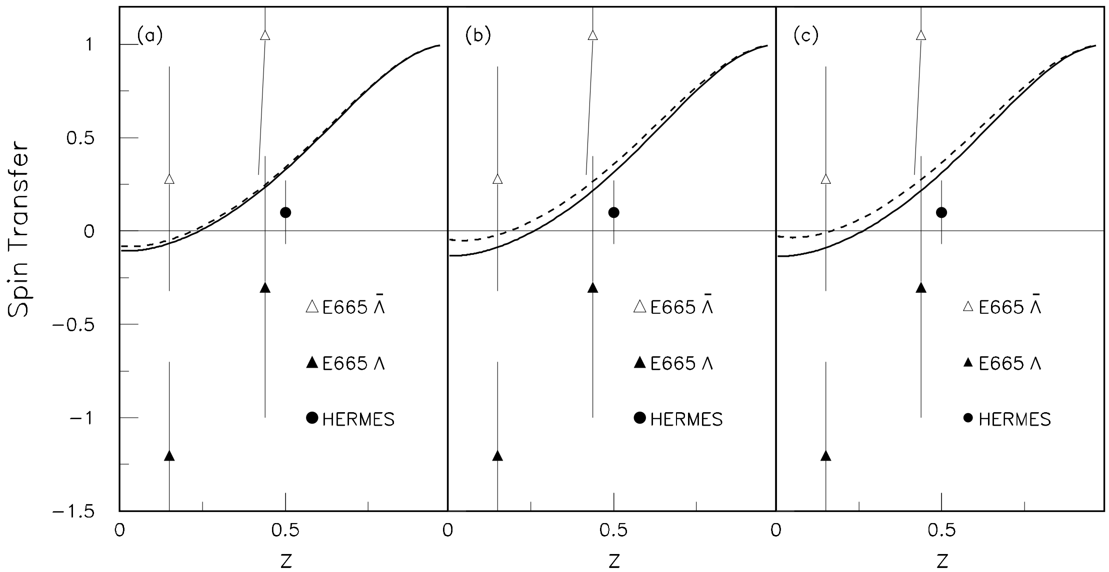

Figure 2: Same as Fig. 1, but the quark to Λ fragmentation functions are predicted by a perturbative QCD (pQCD) based model.

for Λ and $\overline{\Lambda}$ is small in this situation. However, the sea quark-antiquark asymmetry in the quark and antiquark fragmentations to the Λ has been found to be an alternative possibility for the different behaviors of the spin tranfer for Λ and $\overline{\Lambda}$ production [11].

The above discussion helps us to understand why the strange quark-antiquark asymmetry can provide some contribution to the different behavior of Λ and $\overline{\Lambda}$ productions. This possibility can only manifest itself in the specific situation when the strange quarks and antiquarks are important and $\overline{s}(x) > s(x)$. Strictly speaking, there have been many experimental data related to the u and d quark and antiquark distributions so that there should be less freedom to introduce $\epsilon < 0$ for the u and d quarks. However, we notice that a possibility of $\overline{d}(x) > d(x)$ is not completely forbidden in the baryon-meson fluctuation picture to understand the Gottfried sum rule violation [23]. Therefore we consider another case with an additional contribution of

$\overline{d}(x) > d(x)$ in the target proton:

$$\begin{aligned} u &= u_0 + \delta u = 50.32 + 8; \\ d &= d_0 + \delta d = 45.41 - 8; \\ s &= s_0 + \delta s = 17.11 - 8; \\ \overline{u} &= \overline{u}_0 + \delta \overline{u} = 33.55 - 8; \\ \overline{d} &= \overline{d}_0 + \delta \overline{d} = 35.29 + 8; \\ \overline{s} &= \overline{s}_0 + \delta \overline{s} = 17.12 + 8. \end{aligned} \tag{13}$$

The calculated spin transfer for Λ and $\overline{\Lambda}$ production are presented in Figs. 1(c) and 2(c). We find that $\overline{d}(x) > d(x)$ could only provide a very small contribution to the different behaviors of Λ and $\overline{\Lambda}$ productions with fragmentation functions from both the quark-diquark model and the pQCD based model. This is due to the u quark dominance and it also suggests that the Λ and $\overline{\Lambda}$ production at small x is not sensitive to the d and $\overline{d}$ quark distributions, but might be sensitive to the s and $\overline{s}$ quark distributions, although there is strong model-dependence in this conclusion.

From the above general analysis we find that the different behaviors of Λ and $\overline{\Lambda}$ productions could be due to either the quark-antiquark asymmetries in the quark fragmentations and/or in the nucleon sea. The strange-antistrange asymmetry of the nucleon could provide a contribution to the observed difference of Λ and $\overline{\Lambda}$ productions, but the magnitude is still too small to explain the data. It thus forces us to consider the importance of the quark-antiquark asymmetry in the quark fragmentations if the E665 data are confirmed.

However, due to large uncertainties in the data and in the various quark to Λ fragmentation functions, it is still too early for us to arrive at some definite conclusion other than to suggest some interesting possibilities for further study. Thus we still need further efforts in order to reduce the uncertainties in the spin and flavor structure of various quark to Λ fragmentation functions. We know that the Λ and $\overline{\Lambda}$ fragmentation in neutrino (antineutrino) DIS processes [4, 11], and the different combinations of beam and target polarizations in the charged lepton DIS on the nucleon, can provide further insight on this issue, in addition to the Λ ($\overline{\Lambda}$) fragmentation in the e^+e^- annihilation near the Z resonance [10]. We expect further theoretical and

experimental work to push forward progress in this direction.

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